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INVESTIGATION AND DEVELOPMENT OF OPTICAL MODULATORS

by

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ABSTRACT: Since existing optical modulators have electrooptical crystals that require high voltages, a device using a symmetrical Michaelson interferometer with double refracting diagonally cut crystals in the arms was developed. The latter are controlled by a field at right angles to the direction of propagation. The power required to control the modulator can be lowered by increasing the length of the crystal and decreasing its cross section. The power required by the modulator depends on the operating modulation frequency band; when a subcarrier is used, the voltage can be fed to the modulator by a resonance circuit. Curves are plotted for values of power as a function of the modulation band. Optimum adjustments of mirror position are given for maximum uniformity of light intensity over the beam cross section. The arms of the modulator must be identical and temperature must be controlled for best operation since the modulator is rather sensitive to temperature variations. Details on the thermal expansion of various parts and materials are given and the effects of expansion on modulator operation are described. Invar is suggested as the best structural material. The maximum modulation frequency is 500 to 700 Mc. A model of the device, 15 x 15 x 6 cm and weighing 3.6 kg, was constructed of superinvar. Details of the optics are given, including the technique for adjusting the mirrors. The modulator was tested between 0 and 100 Mc with a control voltage of 150 v. The model was tested in an experimental transmission of a television picture with the aid of a laser beam. Calculations were made of waveguide size for given wavelengths and the power required for the crystals in the waveguide. The tests of the modulator based on a Michaelson interferometer proved its applicability for high and superhigh frequencies. Orig. art. has: 5 figures. English Translation: 7 pages.

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U. S. BOARD ON GEOGRAPHIC NAMES TRANSLITERATION SYSTEM

Block	Italic	Transliteration	Block	Italic	Transliteration
А а	<i>А а</i>	A, a	Р р	<i>Р р</i>	R, r
Б б	<i>Б б</i>	B, b	С с	<i>С с</i>	S, s
В в	<i>В в</i>	V, v	Т т	<i>Т т</i>	T, t
Г г	<i>Г г</i>	G, g	У у	<i>У у</i>	U, u
Д д	<i>Д д</i>	D, d	Ф ф	<i>Ф ф</i>	F, f
Е е	<i>Е е</i>	Ye, ye; E, e*	Х х	<i>Х х</i>	Kh, kh
Ж ж	<i>Ж ж</i>	Zh, zh	Ц ц	<i>Ц ц</i>	Ts, ts
З з	<i>З з</i>	Z, z	Ч ч	<i>Ч ч</i>	Ch, ch
И и	<i>И и</i>	I, i	Ш ш	<i>Ш ш</i>	Sh, sh
Я я	<i>Я я</i>	Y, y	Щ щ	<i>Щ щ</i>	Shch, shch
К к	<i>К к</i>	K, k	Ъ ъ	<i>Ъ ъ</i>	"
Л л	<i>Л л</i>	L, l	Ы ы	<i>Ы ы</i>	Y, y
М м	<i>М м</i>	M, m	Ь ь	<i>Ь ь</i>	'
Н н	<i>Н н</i>	N, n	Э э	<i>Э э</i>	E, e
О о	<i>О о</i>	O, o	Ю ю	<i>Ю ю</i>	Yu, yu
П п	<i>П п</i>	P, p	Я я	<i>Я я</i>	Ya, ya

* ye initially, after vowels, and after ъ, ь; e elsewhere.
 When written as ѣ in Russian, transliterate as yě or ě.
 The use of diacritical marks is preferred, but such marks
 may be omitted when expediency dictates.

INVESTIGATION AND DEVELOPMENT OF OPTICAL MODULATORS

I. V. Pirshin, M. M. Koblova, V. I. Khlystov,
and Ye. V. Antonyants

Development of effective circuits for optical modulation presents a sufficiently difficult problem, which up to now has not been solved mainly because the electro-optical crystals used in role of active substance require great control voltages.

A promising circuit [1] appears to be one with the utilization of the symmetrical Michaelson interferometer, in the arms of which there are situated electro-optical KDP¹ (КДП) crystals (Fig. 1) of diagonal cut, controlled by a field which is transverse to the direction of propagation. In this case the value of the voltage necessary for total tuning of this modulator from transparency to darkness is determined not only by activity of the electro-optical material (index of refraction n_0 and electro-optical coefficient r_{63}), but also depends upon the dimensions of the crystals:

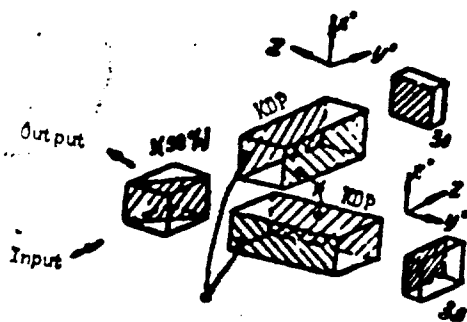


Fig. 1.

$$U_0 = U_{\lambda/2} \frac{a}{2l}. \quad (1)$$

where $U_{\lambda/2} = \frac{\lambda}{2n_0^3 r_{63}}$ - voltage, necessary for obtaining total tuning in the Pokkel's cell; a - transverse dimension of crystal, along which voltage is applied; l - length of crystal.

¹No expansion of this abbreviation was found [Tr. Ed. note].

It is easily seen that by increasing the length of the crystal and by reducing the dimension of section a it is possible to lower the necessary control voltage. However, the reduction in a is limited by the dimension of the diameter d of the light ray. Figure 2 gives curves characterizing the dependence of the voltage amplitude necessary for various diameters of the optical beam to obtain a defined modulation depth when using crystals 50 mm in length.

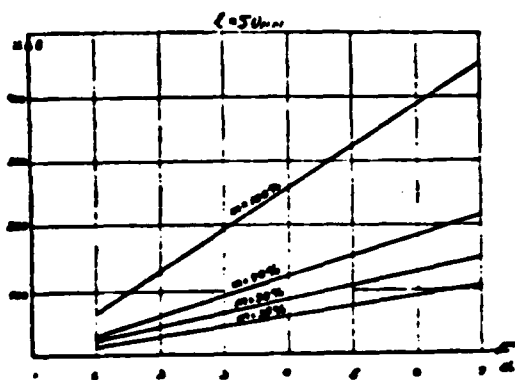


Fig. 2.

The power required by the modulator depends on the modulation frequency band in which the modulator should work. When using a subcarrier frequency for feeding voltage to the modulator it is possible to use a resonance circuit. Then the power of the source should be

$$P = \frac{U^2 C}{Q_0} = U^2 2C \Delta f, \quad (2)$$

where U - voltage, applied to crystals; C - capacitance of modulator (crystals); ω - angular frequency of subcarrier Q_0 - equivalent quality of circuit (with consideration of damping introduced by the source); Δf - given modulation band.

Calculated values of the power required by the modulator in dependence upon the given modulation band are shown in Fig. 3 (for various modulation coefficient values). In this case the capacitance of the modulator with crystals of 50 mm in length is equal 30 pF, and the value of subcarrier frequency is 70 MHz. Thus, at $m = 50\%$ the required power per MHz of the band equals 4.4 W.

We will consider the requirements for modulator tuning accuracy. If one of the mirrors will deviate by a certain angle $\Delta\phi$ (Fig. 4) from the optimum position, then on various parts of beam section there will be obtained different propagation differences, which will lead to an unequal transparency over the section of the beam. The irregularity in half of the band, i.e., the change in transparency from zero to maximum over the beam diameter, will be obtained, if one of mirrors will deviate by angle (see Fig. 4)

$$\Delta\phi = \frac{\lambda}{4D}, \quad (3)$$

where λ - wavelength of light; D - diameter of light beam.

At $D = 2$ mm and $\lambda = 0.63$ μ m the permissible value of $\Delta\phi = 16''$.

In this way the desirable tuning accuracy of interferometer mirrors constitutes several seconds.

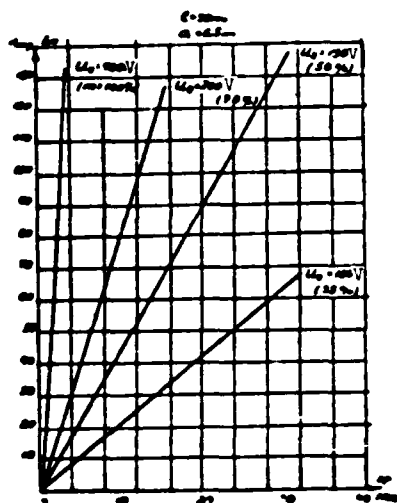


Fig. 3.

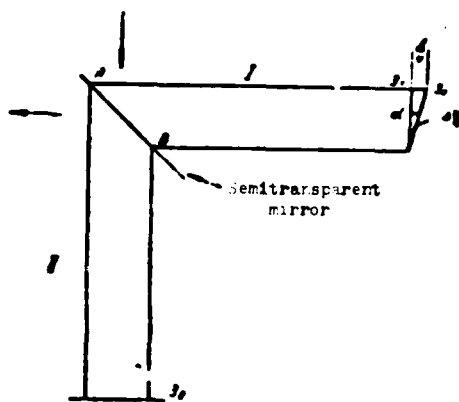


Fig. 4.

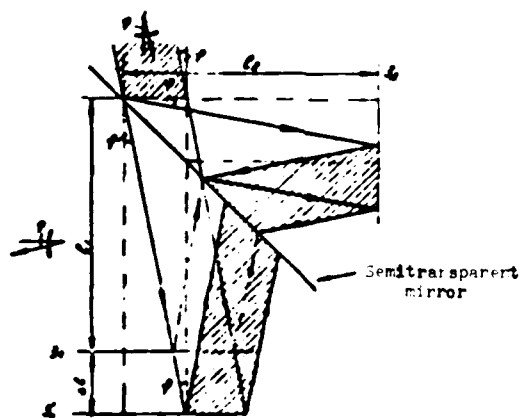


Fig. 5.

It is also necessary that the arms of the modulator be equal. This is caused by the fact that during beam deflection from normal incidence, for example, by angle ϕ (Fig. 5) with an unequal length of arms there will occur modulator tuning (displacement of its operating point along by the transparency curve. Total tuning takes place at a deviation angle ϕ , which is determined from the following equation

$$\left(\frac{nl_1}{\cos \varphi} - \frac{nl_2}{\cos \varphi}\right) - (nl_1 - nl_2) = n(l_1 - l_2)\left(1 + \frac{\varphi^2}{2}\right) -$$

$$- n(l_1 - l_2) = n\Delta l \frac{\varphi^2}{2} = \frac{\lambda}{4},$$

whence

$$\varphi = \sqrt{\frac{\lambda}{2n\Delta l}}. \quad (4)$$

For $\lambda = 0.63 \mu\text{m}$ at $n = 1.51$ and $\Delta l = 10 \mu\text{m}$ this angle will constitute

$$\varphi = \sqrt{\frac{0.63 \cdot 10^{-6}}{2 \cdot 1.51 \cdot 10 \cdot 10^{-6}}} = 8^\circ.$$

Ordinarily the divergence of the laser beam composes fractions of a degree. However, it is possible to work with generators in which beam divergence reaches 1° ; then the inequality of arms cannot be greater than 0.01 mm , in order that less than a tenth fraction of the band will be set over the field.

The requirements for symmetry of the interferometer appear also for the observance of temperature stability. Its contribution to the detuning of the modulator can be introduced by linear expansion of the crystals, and by a change in the index of refraction of the crystal due to temperature.

At a temperature change by dt° there will occur a change in the difference in length of the crystals by $(l_2 - l_1)\alpha dt$, where α — is the coefficient of linear expansion. Furthermore, the refraction index will obtain the increment $\beta n dt$. The total change in difference in optical arm lengths on account of the crystals will constitute

$$\Delta L = n\Delta l \alpha dt + \Delta l \beta n dt. \quad (5)$$

For one total tuning should be $dL = \frac{\lambda}{4}$. At $n = 1.51$, $\Delta l = 0.2 \text{ mm}$,

$\alpha = 3 \cdot 10^{-5}$, $\beta = 10^{-4}$ a temperature change of several degrees is sufficient for total tuning of the modulator. If one tuning is permitted during a temperature change from -60 to $+60^\circ$ (120°C), then Δl in the crystals should be less than $10 \mu\text{m}$. The length of interferometer arms depends upon the position of the mirrors which are fastened in the body. If the distances from the center cube prism to the mirrors are inaccurate (with a difference Δl), then temperature oscillations will be reflected in the tuning because the difference in optical arm lengths at a temperature change by dt will change to

$$\Delta L_{\text{tot}} = \Delta L_{\text{cr}} + \Delta L_{\text{sp}} dt. \quad (6)$$

For total tuning in the range of temperatures $dt = 120^\circ$ with the

manufacture of the body from brass ($\alpha = 0.2 \cdot 10^{-4}$) the permissible arm difference is equal to

$$\Delta l_{\text{max}} = \frac{\lambda}{4 \alpha_{\text{max}} dt} = \frac{0.63 \cdot 10^{-3}}{4 \cdot 2 \cdot 10^{-4} \cdot 120} = 0.06 \text{ mm.}$$

When the body is manufactured from glass ($\alpha = 5 \cdot 10^{-6}$) $\Delta l_{\text{kop}} = 0.3 \text{ mm}$, and for a body from Invar ($\alpha = 1 \cdot 10^{-6}$) $\Delta l_{\text{kop}} = 1.5 \text{ mm}$. In this way, having prepared the modulator body from Invar and using crystals differing in length by not more than $10 \text{ } \mu\text{m}$, it is possible to obtain stable work of modulator in the range of temperatures.

With use in the modulator of laminar electrodes clamped to the edges of the crystal, at high modulation frequencies it is necessary to consider the final time of light propagation through the crystal, comparable with the period of voltage modulation. The field distribution along the crystal obtained in this case decreases the depth of modulation at high frequencies. Pursuing the reduction of m by $\Delta m = 10\%$, we obtain a maximum modulation frequency $F = 500 \text{ to } 700 \text{ MHz}$.

The mockup of the modulator was made on the basis of a superinvar body. In the summit of right angle of the body is fastened a cube prism with a semitransparent mirror. By the legs along the walls are situated KDP crystals with a length of 50 mm . The transverse section of the crystals is square can also equal from $3 \text{ mm} \times 3 \text{ mm}$ to $7 \text{ mm} \times 7 \text{ mm}$. The ends of the crystals are protected by glasses on a semioptical contact.¹ The sides of the crystals, to which are applied flat electrodes, are covered by silver paint. Crystal sides not protected by electrodes and glasses are covered by varnish EMKHS-77 (ЭМХС-77). Reflecting mirrors are fastened in pivots whose axes of rotation are orthogonal. Rotation of the mirrors is realized with the aid of two screws with fine thread. By relieving one screw and screwing in the other, it is easy to turn journal around the axis. Pivots and screws were made, like the body, from superinvar.

In such an execution the modulator is applied during work on a subcarrier frequency, which lies above 10 MHz . In case the modulator has to be used for video modulation and the control frequencies lie below 10 MHz , the electro-optical crystals together with electrodes are covered on all sides with PU-2 (PY-2) glue. Only the protected glasses at the ends remain exposed. In this case the piezoelectric resonances, connected with the dimensions of the sample and disturbing the uniformity of modulation characteristic at low frequencies, do not appear.

The modulator has small dimensions: $15 \text{ cm} \times 15 \text{ cm} \times 6 \text{ cm}$. Its weight is 3.6 kg .

¹Protected modulation elements made from KDP crystals were prepared by the IK of the Academy of Sciences USSR.

Modulator tests were made at a range of frequencies of 0-100 MHz at a control voltage amplitude of 150 V. With consideration of the characteristic of the FEU-36 (ФЭУ-36) (which was used during the measurements) it is found that the depth of modulation does not change with frequency and is approximately 40%. (During the experiment we used KDP crystals with a ratio $\frac{2l}{a} = 15.4$).

A modulator was used in the experiment in the transmission of a television image with the aid of a laser beam.

In the optical range there is promise in the application of shf modulation, because thanks to the high value of subcarrier frequency it is easy to realize the potential broadbandness of optical communication lines. On shf a modulator on the Michaelson interferometer can be realized by arranging waveguides or resonators with electro-optical crystals in the interferometer arms. The most suitable in this case appears to be the use of a diagonal crystal cut with transverse control field. Since the frequency of the field acting on the crystal in this case is great and the time within which the light travels over the crystal is commensurable with the shf period, it is necessary to equalize phase velocities of light and shf ($V_\omega = V_\Omega$), and also to arrange the mirrors at a definite distance from the crystals. The dimensions of waveguide and crystal are easily calculated in this case.

The standing wave in the resonator can be presented in shf form of a straight and reflected wave, and during the arrangement of shf resonators in the arms of the interferometer the interaction of light will be realized both with the straight and with reflected shf waves, since the optical beam propagates both in straight and inverse (after reflection from the mirrors) directions. In this way if condition $V_\omega = V_\Omega$ is observed, no limitations are imposed on the length of the electro-optical crystal.

The speed of light during propagation in the KDP crystal equals $V_\omega = \frac{c}{n_{11}} = \frac{c}{1.51}$ (n_{11} - index of refraction by axes x' and y'), and, consequently, the deceleration of shf wave in the waveguide with KDP crystal should be equal to $\frac{V_\Omega}{V_\omega} = 1.51$. Calculations were made allowing for defined KDP and ADP (АДП) crystal thicknesses to find the dimension a of waveguide at which there is realized the necessary deceleration by 1.51 times on waves $\lambda_0 = 3.2$ cm and $\lambda_0 = 9.75$ cm. Calculations were also carried out on the determination of shf power, necessary for the generation of a definite voltage acting on the crystals situated in the waveguide.

At KDP crystal thicknesses $t = 1.5$ mm and waveguide width $a = 5$ mm the power corresponding to voltage amplitude $U_0 = 300$ V equals 19.5 W. When employing a resonator with a quality of the order

of several tens, the shf power necessary to control the modulator should be smaller. In this case modulation frequency band can be equal to several hundreds of megacycles per second.

A modulator on the Michaelson interferometer realized with shf resonators, where the KDP crystals were controlled by a field E longitudinal to the direction of shf propagation. Two experiments were made. In the first the shf field was fed to one resonator, in the second - into both resonators, situated on both interferometer arms. The shf power in the resonators was fed in the opposite phase. The power gain during the use of two resonators in comparison with one is close to 2.

Investigation of modulator on the Michaelson interferometer showed the promise of developing such a circuit for controlling high and ultrahigh frequencies.

Literature

1. Pirshin I. V. Ispol'zovaniye elektricheskogo effekta v interferometre Maykel'sona dlya modulyatsii sveta (Use of the electrical effect in the Michaelson interferometer for modulation of light). "Radiotekhnika i elektronika", 1965, No. 12, str. 2237-2241.